Increasing Performance and Added Capabilities of USNA Sail-Powered Autonomous Surface Vessels (ASV)

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USNA SailBot #3

***Abstract*— This paper details the USNA SailBot research and development since the 2009 competitions. The 2009 boat was designed for light air and flat water, which it excelled in, but it was unsatisfactory in higher winds and waves. In contrast, the 2010 boat was designed for long passages while meeting the SailBot class rules. Research behind the design is presented, highlighting the changes between the second and third generations of USNA SailBots. These include a new hull, keel, bulb and rudder designs along with navigation, winch, communications, collision avoidance and power management systems.**

***Keywords*— autonomous surface vessel, SailBot, velocity prediction program (VPP)**

I. Introduction

Autonomous surface vessels (ASV) provide opportunities in surveillance, monitoring and oceanographic research. In 2004, Erik Berzins, an engineering student at the University of British Columbia developed a small sail-powered ASV. From that developed the SailBot competitions held in 2006, 2008 and 2009. The competition rules limit boats in the SailBot Class to two meters in length, three meters in beam (allowing for multihulls), 1.5 meters in draft and 5 meters in height from the bottom of the keel to the top of the fixed mast (not including wind instruments)[1]. The relatively small size allows for easy transportation and handling on shore while also keeping the construction and shipping costs down. Competition is intended for undergraduate students and the contests include a design presentation along with on-the-water events that test navigation, station keeping, performance and endurance[2].

As described in reference [3], the United States Naval Academy (USNA) started a team in 2007. The USNA team comprises students majoring in naval architecture and systems engineering. In each year since, the midshipmen have designed, built and competed in the International SailBot Regatta and in 2009 also participated in the World Robotic Sailing Championship (WRSC).

While the primary mission statement for all three boats was to win the SailBot competition, the team has a secondary goal to develop a small, sail-powered ASV for long distance passages and oceanographic research. Boat #3 is the first concerted effort by the team to that goal. Each year the team spends approximately US$8000 on developing a boat.

II. Naval Architecture

As reference [3] describes the transition from Boat #1 to Boat #2, this paper will focus on the development of Boat #3. The hulls, keels, rigs and sails are named according to their chronological design and construction.

Table 1 shows the three boats' principal characteristics with their largest sails. The influence of the SailBot Class rules is

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14. ABSTRACT
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clearly seen in that the boats' designs reflect the performance enhancing characteristics of maximum length and stability.

TABLE I
PRINCIPAL CHARACTERISTICS OF THREE USNA SAILBOTS

		Boat 1	Boat 2	Boat 3
LOA	m	2	2	2
LWL	m	2	2	2
Beam	m	0.36	0.28	0.305
Draft	m	1.5	1.5	1.5
Depth	m	0.23	0.23	0.31
Sail Area	m2	3.1	3.1	3.1
Disp	kg	26.7	24	29.9
Cp		0.57	0.54	0.56
LCB		53%	55%	55%
LCF		55%	57%	58%
"SA/Disp"		34.9	37.5	32.4
"L/Disp"		6.7	7.0	6.5

Boat 2 was optimized toward the conditions expected at SailBot 2009; light air and flat water ($h_{1/3}$ <0.25m), and she performed well in those conditions, winning the competition. Her shortcomings were apparent at the WRSC competition in Portugal, which featured winds to 25 knots and $h_{1/3}$ ~ 1m. Her low freeboard meant that her bow frequently submerged, increasing drag significantly and losing directional control. Her relatively flexible keel meant that she lost potential righting moment. The stronger winds also pointed out her mast should be stiffer. The larger wave amplitude also pointed out the need for a radio mast as communications were lost when the deck-mounted antennas were in the bottom of a wave trough.

These lessons learned helped guide the 2009-2010 team in their research and design activities. Rig 4 was developed as a simpler alternative to the double-spreader swept rigs (#1-3) and features a free-standing mast with wishboom, similar to those on the Wylie-Cat style of recreational sailboats [4]. Aluminum tubes bonded in the hull near the bow serve as the mast step in a way similar to those on Laser Class sailboats. The advantage to this rig style is the ability to have the relatively flexible mast bend significantly in wind gusts, thus depowering the sail. This means that a larger sail is possible, increasing performance in light winds and allowing for a wider range of acceptable wind speeds. The disadvantage is the need for an anemometer that is compatible with large masthead bend angles and the difficulty in finding the correct mast bend profile and matching it with a sail design. Figure 1 shows Boat #2 with Rig #4. The initial iteration exhibited too much mast bend, so it was stiffened through the use of extra internal carbon tubes. It performed well in limited trials but due to time constraints the rig has not seen the same level of development as the standard rig. The team plans to continue its experimentation with the concept.

Rig #5 features iterative developments from Rigs #1-3. A mast step key was added to reduce rig twist. Larger diameter carbon tubing (dia = 16mm, t_w = 5 mm) was used which increased the tube stiffness 19% from Rig #3. For ease of construction and durability the carbon fiber main and jib booms were replaced with aluminium with negligible weight impact.

The team was tasked with the development of a hull that would maintain the light air performance of Boat #2 while improving on the seaworthiness and durability. As with the previous teams the primary tool was a spreadsheet-based velocity prediction program (VPP) named "PCSail" [5]. While the VPP runs are quick, realistic trade-off studies are time-intensive as a change in one hull variable necessitates changes in many others. For instance, an increase in beam requires a canoe body draft reduction to maintain constant displacement. That means that a new hull is designed for each data point. A complicating factor is the wide wind range which requires a design that is good across the full range. Boats #1 and #2 were designed for winds from 0-15 knots, while Boat #3 is designed for 0-30 knots.

Fig.1 Freestanding Rig 4 with wishboom on Boat #2

This year's studies included variations in waterline beam, displacement, freeboard and prismatic coefficient. Each student performed a study in a concentrated area that they presented to the class. With that data all students then took the findings and developed their own hull shapes. These were compared in a "virtual regatta" to determine the best hull design. Interestingly, three of the seven hulls had essentially the same potential, but each had some design feature that reduced its potential. A compromise hull developed from the three best hulls gave a better performing hull shape.

Boat #2's characteristics were the baseline, but were immediately modified to include a minimum forward freeboard of 200 mm, (Boat #2's was 130) to improve seaworthiness, which was based on video review of the Boat #2 sailing and nosediving, in waves. Another design boundary was a minimum deck beam of 305 mm to accommodate Holt Allen HA 637 watertight hatches. That decision was based on the user-friendliness of large diameter, quick action hatches.

The first study looked at beam, assuming a wall-sided vessel. For each case the displacement was fixed at 27 kg and the waterline length at 2 meters. The canoe body draft varied inversely with waterline beam, although with some variation based on varying the midship coefficient. As stability decreases with narrowing waterline beam, the righting moment was adjusted accordingly. The composite Time Around Course was calculated using a circular race course sailed in winds of 9, 12, and 20 knots. Figure 2 shows the results from 28 beam variations.

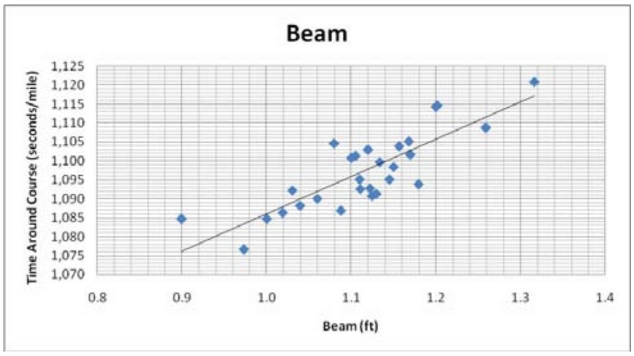

Fig. 2 Beam at the deck variations showing the increase in performance as beam decreases. Boat #3's deck beam is 305 mm (1.0 ft) with the waterline beam 224 mm (0.74 ft).

To determine the impact of increasing the canoe body draft, a complementary series to the maximum beam study was completed. This gave a better understanding of the relationship between waterline beam and canoe body draft while holding displacement, maximum beam and length constant. The results, shown in Figure 3, showed that decreasing waterline beam while increasing canoe body draft also improved performance.

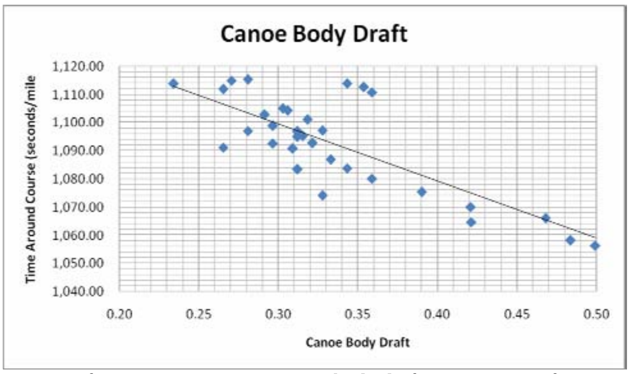

Fig. 3 Performance increases as canoe body draft increases as a function of waterline beam decreasing. Boat #3 has a canoe body draft of 113 mm (0.37 ft in above plot)

As one goal of Boat #3 was to improve its seaworthiness, an increase in freeboard was desired. Figure 4 shows the results of freeboard variations, with inconclusive results on performance. As freeboard increases, the center of gravity and weight increase, decreasing the vessel's performance. On the other hand, the higher freeboard also decreases drag associated with deck submergence. Across the expected wind range and wave height the changes appeared to balance each other. As directional stability is negatively impacted by deck submergence, Boat #3 was designed with 200 mm freeboard at the bow and an average freeboard of 169 mm.

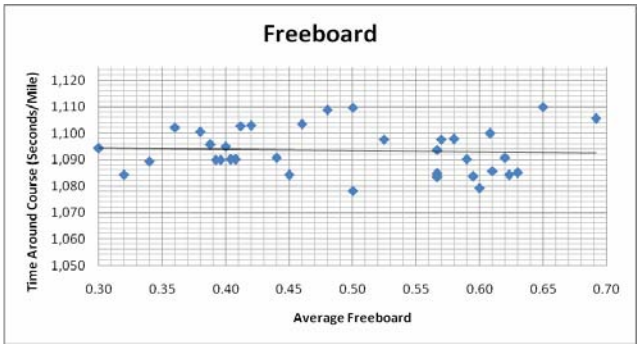

Fig. 4 Increasing the average freeboard reduced drag but also decreased stability, resulting in no significant change in performance within the range studied. Boat #3's average freeboard is 169 mm (0.55 ft).

With the goal of a more seaworthy and durable boat designed for stronger winds and higher seas, Boat #3 was anticipated to displace more than Boat #2's 26.7 kg. Recognizing that more freeboard automatically increases structural weight and decreases stability, a minimum weight increase of 0.4 kg was expected. In addition, knowing that the Airmar weather station weighs 0.4 kg more than the potentiometer and a stiffer keel would weigh more, the total expected weight gain was going to be at least 1.5 kg. A study of the impact on performance of the displacement increase included a trade-off of the expected hull and keel weight increases and adding weight to the bulb. The variations included adjustments to the righting moment for variations in added structural weight as well as variations in keel deflections. A summary plot of all variations is shown in Figure 5. The target displacement for Boat #3 was 28.2 kg (62.1 lbf), however the as-built displacement was 30 kg (66.1 lbf).

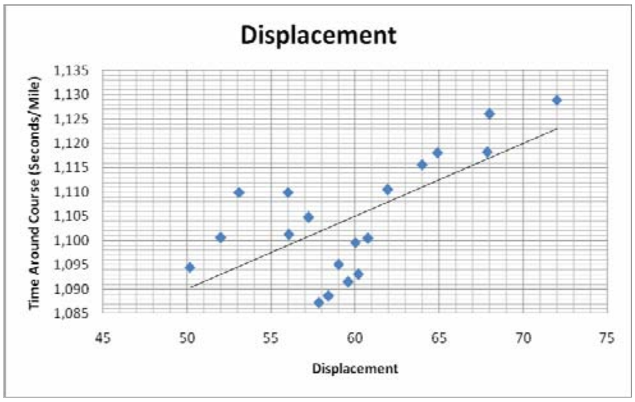

Fig. 5 Performance impact for variations in displacement. Righting moment reflected changes in structural weight with most weight going to the bulb. The target displacment for Boat #3 was 28.1 kg (62 lbf)

The final VPP study (Fig. 6) looked at the prismatic coefficient. The prismatic reflects the distribution of volume along the vessel's length, with a higher number indicating more fullness in the ends. The trend was to a prismatic of 0.56, which was the target value. Due to the plumb ends and flare at the transom, on Boat #3 the prismatic increases with sinkage. At the actual displacement the prismatic is approximately 0.59.

The nearly 2 kg (7%) weight gain was attributed to various factors, including a 1 kg heavier bulb than estimated (due to a greater density of lead shot in the lead/epoxy mixture), a heavier keel than estimated (0.3 kg) and the addition of tank tops (0.3 kg) for gear placement. The remaining extra weight was due to additional structural weight for reinforcements. The narrow waterline beam also produced a relatively small waterplane area which meant that the sinkage for a given weight increase was relatively larger. More sinkage leads to reduced performance and increased control issues. The final sinkage over the designed draft was 11 mm.

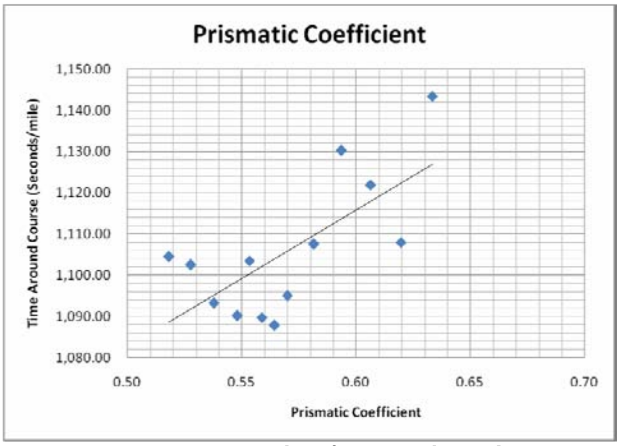

Fig. 6 Variations in prismatic with performance. The trend was to 0.56.

The final hull design selected for Boat #3 contained the best features of the students' designs and was predicted by the VPP to have an average performance improvement over Boat #2 of 3.3% with the crossover wind speed for better performance occuring near 6 knots. At the as-built weight however the performance increase reduced to 1.6% with a crossover windspeed of 9 knots. Figure 7 shows a perspective and body plan for Boat #3. The flare caused by the deck beam constraint, minimum waterline beam and deep canoe body are evident. The entry angle was minimized to reduce wave making resistance and the deck beam forward of midships was minimized to reduce resistance in waves.

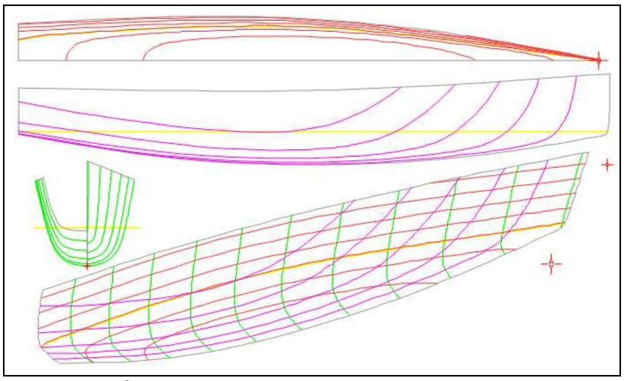

Fig. 7 Lines of Boat #3

New rudder and keel designs were completed based on evolutions from Rudder #3 and Keel #3. For Rudder #4 a conservative approach to rudder loading and an increased emphasis on durability led to a selection of a 12 mm silicon bronze shaft to replace the 9.5 mm 316L shaft in Rudder #3. The increased rudder shaft diameter forced a larger root thickness. Based on sailing trials, Rudder #2 was deemed to have too little rudder area (550 cm^2) for the larger sail areas currently used and rudder #3 was built with an area of 740 cm^2 just days prior to WRSC 2009. That rudder easily controlled Boat #2 but showed signs of over-correcting. Rudder #3 was designed with 632 cm^2 and in limited sea trials appear to control the boat well. Figure 8 shows the rudder, shaft and control linkage.

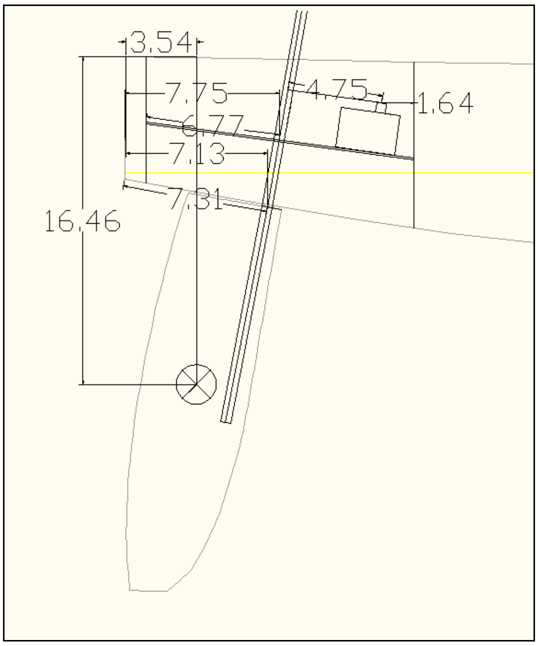

Fig. 8 Rudder #4 (dimensions in inches)

Keel #4 also evolved from previous keels. Keel #2 had acceptable deflections and strength, but more surface area than desired. Keel #3, while strong enough, deflected to leeward approximately 190 mm when sailing upwind in strong winds. On the other hand it had relatively little wetted area. The large deflection unfortunately resulted in significant loss in righting moment. In addition, the slight imbalance between the rotational center and the center of gravity created a twist of up to 2.5 degrees when heeled 30 degrees, creating unnecessary drag. The criteria for the new keel was a maximum deflection of 90 mm when heeled 30 degrees, with no more than 1.2 degrees twist. Following the trend of designing for long distance sailing the keel was moved to the forward edge of the bulb to aid in weed shedding. This did cause a slight increase in drag and forced the keel and rig further forward in the boat.

The final keel design has a root chord of 90 mm, a tip chord of 52 mm and varies in thickness from 13.5% at the root to 14% at the tip. A 12 x 12 mm bar is welded to the bottom to act as support for the bulb. 17-4-ph H1150 was again used as the fin material and the deflections and stresses were checked with FEA, resulting in a peak stress of 230 MPa. The bulb is a NACA0014 section with a squash ratio of 1.5 and a beaver tail. As the rudder, keel and bulb all operate in the laminar region the turbulent NACA00 series was chosen due to the forward position of maximum area compared to laminar sections.

Due to watertight integrity issues with Boat #2, Boat #3 was designed with as few leak paths as possible. The chainplates are laminated to the outside of the hull and all fittings are tapped to G-10 backing plates rather than through bolted. During the initial flotation test she was submerged for two minutes with the deck 0.25 meter below the water surface with no water ingression noted. Lifting handles were added for convenience.

While the WRSC 2010 regatta will point out numerous potential improvements, the next team of USNA SailBot naval architects will certainly build more weight margin in to their design!

III. Systems Engineering

The primary objectives of the 2010 systems engineering program was focused on manoeuvrability, durability, reliability and controllability of SailBot. The systems needed to be user friendly and adaptable to the multiple USNA boats. Design specifications were developed to meet the twin goals of competing in WRSC 2010 and accomplishing an unassisted voyage from Norfolk, VA to Annapolis, MD. Specifically, controls were improving through better sensor data, and providing an on-board power generation system.

The functional block diagram for Boat #3 is shown in Figure 8. From Boat #2 the changes include solar charging, the replacement of the potentiometer anemometer with the Airmar PB200 ultrasonic weather station. Although the potentiometer wind sensor seen in reference [3] was relatively inexpensive yet reliable and has a low power budget, the PB200 has no moving parts to fail over long transits, and can calculate true and apparent wind directions. It also contains a GPS and a 3-axis compass. As with Boat #2, all components are located in watertight boxes in case the primary hull seals are compromised.

The Rabbit 3000 Navigation Board is responsible for receiving the output from the Airmar and converting it into variables for the control code. The microprocessor uses the control code and variables to determine the best course of action and outputs the rudder and sail winch commands. An Xbee extension located in the antenna mast allows wireless programming of the boat.

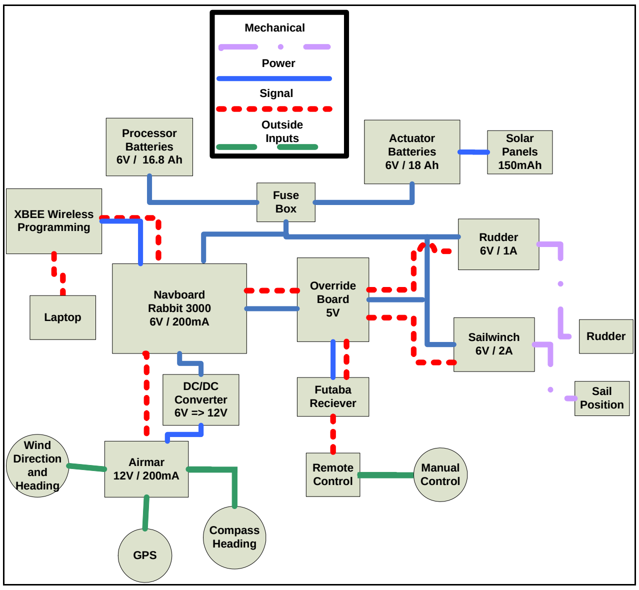

Fig. 8 Functional Block Diagram for Boat #3

Reference [3] laid out the basic control code that was used. Updates where made to how the boats are controlled when beating to windward and to reflect the new wind sensor. Originally, port and starboard close hauled courses where calculated and the control code steered the boat to a heading. This method required a very accurate true wind direction reading, which we were not able to acquire. Our solution was to sail closed hauled courses based not on heading but on apparent wind angles. Now when sailing upwind, the boat steers to maintain a predetermined apparent wind angle. This method has proven to be very effective with the old potentiometer wind sensor, and also with the Airmar.

The code to decipher the Airmar output is located in a costate in the main function. This allows the Airmar to update at its own pace independent of the control code. The first lines of the Airmar costate read in the sentences from the NavBoard. The code scans the NMEA 0183 sentences for its headers and then saves the corresponding data to the proper global variables.

Solar panel charging was designed into the system using an off-the-shelf waterproof 150mA 12V panel with a 12v-6v DC/DC converter. Size of the panel and the heat generated in the converter were issues and a switch to multiple, smaller 6V, 100mA, panels (SolLite-4AAE) is expected. Testing of the panel showed great tolerance to heel angle due to reflected light. This indicated that a fixed mount on deck would be acceptable, removing the need for a gimbled or angled mount.

As the SailBots are autonomous, an on-board collision avoidance method is desirable. Collision avoidance methods were broken into two sub categories: avoiding fixed, stationary objects, and second, avoiding moving objects.

Avoiding stationary objects primarily includes not running ashore, aground, or into a sea wall. During the long distance event at the 2009 SailBot Competition, the course was challenging because although all marks were interconnected via navigable water, in certain wind conditions boats had the possibility to run out of navigable water while tacking upwind. To prevent running aground, danger bearings were used. A danger bearing is a bearing to a specific point, which requires a certain action once your position has passed that bearing. Shown in Figure 9, a danger bearing was established from a fixed point. Once the boat passed a bearing of 141 degrees magnetic it was required to tack. A similar danger bearing was used on the opposite shore. Danger bearings are a relatively simple, non-data intensive way of avoiding large stationary obstacles. Avoiding moving objects presents a separate problem.

Avoiding moving objects requires some kind of sensor to alert the boat of an incoming danger, along with methodology of what the boat should do to avoid that danger. Our goal was to be able to simply detect an object immediately in front of SailBot, and then turn the boat to avoid the danger. When picking a sensor, we primarily required the sensor to be waterproof with low power consumption. We picked the XL-Maxsonar WR1 Ultrasonic Range Finder, seen in Figure 10.

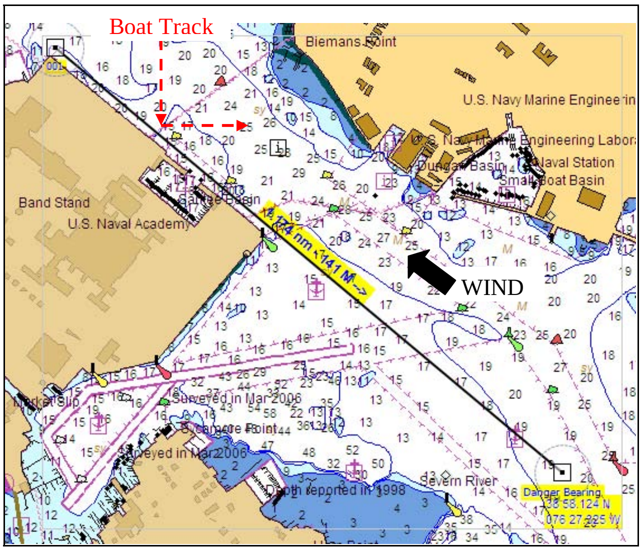

Fig. 9 Danger bearing used on Boat #2 at SailBot 2009


Fig. 10 XL-Maxsonar WR1 Ultrasonic Range Finder [6]

This devise meets IP67 water intrusion requirements, runs on 5 volts with a 20mA current pull. The devise is rated to detect a 0.3 meter wide board 7.5 mters away, within a 1.5 meter envelope in front of the sensor. Although SailBot sails fast (approx 6 kts.) she is small and very maneuverable and thus could avoid an object sensed 7 meters in front of her.

IV. Conclusion

This paper highlighted the continuing development of the "SailBots" by the students at the United States Naval Academy and pointed out the improvements made to take the boats from inshore racers to more capable coastal designs. In addition to the educational objectives reached through the boats' design and construction, the SailBot and WRSC competitions have encouraged more rapid development of the vessels and will encourage others to participate.

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